the structure's roof. The poles, therefore, are expected to effectively divert large-to-severe amplitude return strokes away from the numerous rooftop points of entry.

Hasbrouck is gratified that the DAF lightning study provided an opportunity to apply the concepts put forth in the guidance document. By employing radio-frequency penetration testing, it was possible to identify how and how much lightning energy would leak through "holes" in what the lightning protection code would have judged to be a solid facility. He notes that a 1993 lightning study of DOE's Pantex facility also recommended that some form of penetration radio-frequency testing be carried out in the future.

"Lightning knowledge," he emphasizes, "is neither archaic nor arcane. We cannot prevent lightning, but knowledge of it can help us enhance safety, protecting us and costly property against its damaging and potentially catastrophic effects."

Key Words: hazard management, lightning, radio-frequency testing.

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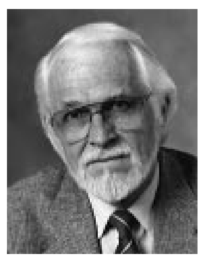
For further information contact Richard Hasbrouck (510) 422-1256 (hasbrouck1@llnl.gov) or Kartik Majumdar (510) 422-5060 (majumdar1@llnl.gov). For information on the Device Assembly Facility study, contact Richard Zacharias (510) 423-0714 (zacharias1@llnl.gov).

About the Engineer

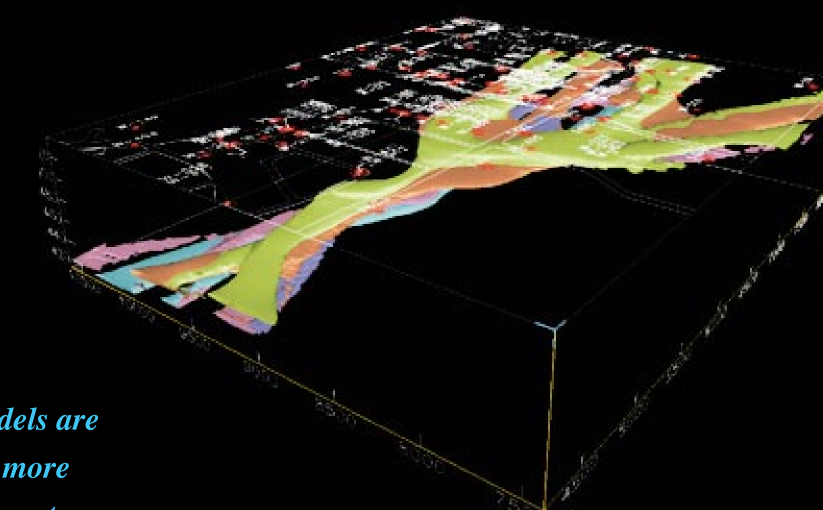


RICHARD HASBROUCK holds a B.S. in electrical engineering and is a Registered Professional Engineer in California. He joined the Laboratory in 1968 and is currently a senior electronics engineer. During his career at Lawrence Livermore, he has supported various projects in the test program. Involvement in nuclear explosive safety studies led to his study of lightning safety, culminating in the lightning hazard management concept. He has written numerous papers and reports on this subject and is co-author of the draft "Lightning Hazard Management Guide for DOE Facilities" (1995). Hasbrouck is a consultant and co-director for engineering of the National Lightning Safety Institute.

In a collateral Laboratory assignment, he is the aviation project officer responsible for the aviation safety interface between Lawrence Livermore and the DOE on Laboratory projects related to aviation, and he was general manager of the Laboratory's F-27F aircraft operation. Prior to joining the Laboratory, he designed, tested, and fielded electro-optical, instrument servomechanisms for astronaut training simulators produced by Farrand Optical Co. in New York for NASA's Project Apollo.

Groundwater Modeling: More Cost-Effective Cleanup by Design

Computer modeling is proving its usefulness as cleanup of contaminated groundwater proceeds at the Livermore site. Modeling is an extremely effective tool for deciding where and how groundwater remediation efforts should be directed. Our models are being made available to others for more efficient remediation around the country.



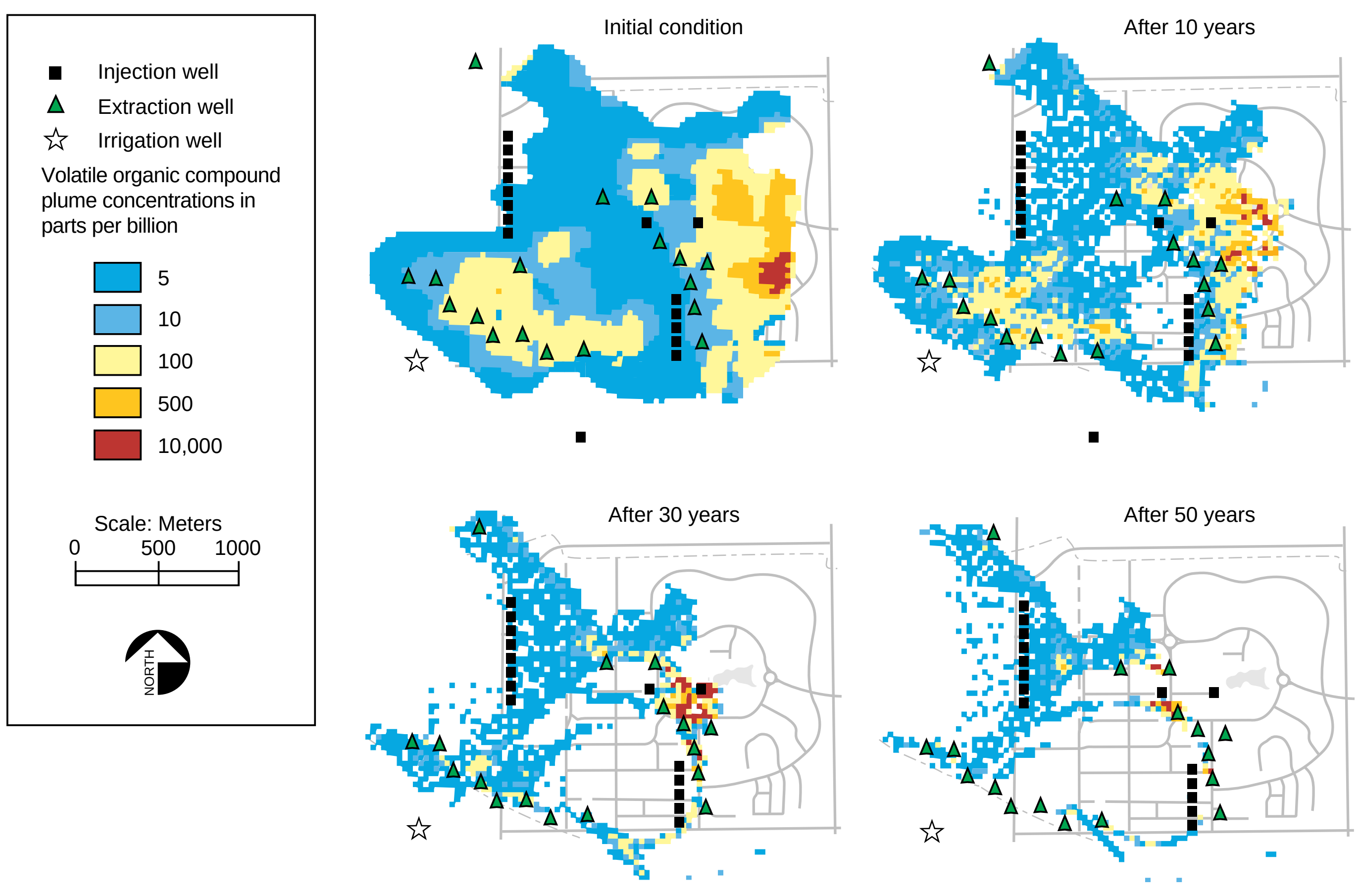
GROUNDWATER modeling uses mathematical methods to help scientists "see" what is happening underground, to make up for what we cannot see with our own eyes. The discipline of groundwater modeling has been around for at least 25 years, but with the powerful desktop computers and advanced software available today, computational modeling is an easier and more effective task than it used to be. Evaluation processes that used to take days or even many weeks can now be done in minutes and often with a higher degree of accuracy.

We have developed several new software tools that can be used by groundwater remediation planners anywhere. MapIt, for example, can read a variety of one-, two-, and three-dimensional data sources and will allow remediation planners to rapidly produce input files for the various simulation codes. With MapIt, we have reduced the time needed to regrid and execute new three-dimensional conceptualizations from months to hours. In the past, a different "code preparation" program was required for each groundwater simulation code. Another tool is PLANET, an easy-to-use, point-and-click, drag-and-drop program that replaces laborious, manual operation of modeling codes to evaluate alternative remediation scenarios (Figure 1). Using these and other newly developed tools, groundwater scientists or engineers at Lawrence Livermore National Laboratory and elsewhere can quickly prepare and simulate robust three-dimensional conceptual models of our site.

We now have the ability to simulate groundwater flow and transport in a large number of possible configurations of a collection of wells (known as a well field) used to extract contaminated groundwater from the subsurface. This ability is a key to finding an optimal remedial system design or designs. Conventional methods of formal optimization can practically consider only a few hundred simulations of possible well field configurations, whereas thousands or even millions of possible configurations are needed to find the most effective designs. As a result, the use of conventional formal optimization methods seems impractical and in need of a new approach.

New methods enable us to quickly evaluate millions of prospective engineering designs and optimize remediation pumping strategies. These methods use artificial neural network (ANN) technology to process a much smaller set of simulations, repeatedly, for any and all configurations. ANNs, whose development was inspired by studies of the human brain, can be "trained" to predict the cost, extracted mass, and containment information that a model simulation normally generates. ANN speed is remarkable—the technology can evaluate thousands of well configurations per second. With ANNs to repeatedly predict outcomes for a particular well field, a genetic algorithm, inspired by evolutionary concepts such as natural selection, directs the search for the best well fields to meet remediation goals.

Figure 1. PLANET, graphical user interface software we have developed, can be used by groundwater remediation planners at any site to examine various contamination extraction and injection scenarios. This two-dimensional simulation of a possible cleanup scenario for the Livermore site shows how concentrations of volatile organic compounds would decline over time.



Scientists at Lawrence Livermore have been developing and using advanced numerical modeling techniques for decades because the design of nuclear weapons requires extensive modeling prior to testing. It made sense, when groundwater contamination was discovered, for our in-house researchers to continue modeling, albeit this time with a very different goal.

Why We Model

We have known since 1983 that there are contaminants in groundwater beneath the Livermore site. (See the box on top right.) But we can only see the soil and water beneath the Laboratory in small, drilled samples of soil and in water samples taken from monitor wells. Because we cannot take core samples of the Laboratory's entire subsurface or cover the site with monitor wells, there are large gaps in our data.

How have we determined the best way to clean up this uncertain environment? And how long it will take? As described in the box on the bottom right, groundwater modeling allows scientists to develop a picture of the workings of an otherwise invisible subsurface. Using computer simulations of the flow and movement of groundwater contaminants, we can evaluate the migration rates and paths of contaminants in groundwater and soil, assess potential health risks, select extraction and injection well locations, and optimize hydraulic control and contaminant removal in our remediation designs.

Modeled simulations of groundwater behavior have served as an effective decision-support tool for Laboratory scientists and engineers in our efforts to clean up contaminated groundwater at the Livermore site as quickly and inexpensively as possible. Modeling provides a means of rapidly retrieving

Groundwater Contamination at the Laboratory

The contamination at the Livermore site consists of widely distributed plumes of several volatile organic compounds (VOCs), tritium, fuel hydrocarbons, and some heavy metals. Some of this contamination has traveled in groundwater off site, especially on the south and west sides of the Livermore site. Contamination was discovered in 1983, and Livermore was declared a Superfund site in 1987.*

The standard method for handling groundwater contamination is to extract the contaminated groundwater and treat it. Known as "pump and treat," this method is very slow. Laboratory scientists have therefore seized the initiative to develop fast, inexpensive, innovative site restoration technologies that can also be applied elsewhere and to demonstrate these technologies at a Superfund site. Restoration activities at the Laboratory to date have centered on a smart pump-and-treat philosophy that includes detailed characterization, validated modeling, phased implementation of remediation, directed extraction, and adaptive, time-managed pumping. The Laboratory has also used underground steam stripping, electrical heating, and vacuum extraction methods to treat the gasoline contamination. Other technologies being studied include abiotic, microbial, and thermal oxidation.

In late 1995, environmental regulatory agencies declared soil cleanup above the water table to be complete at the site of an underground gasoline spill. This is the first formal regulatory closure of a nonexcavation cleanup activity at the Livermore site since cleanup began in 1988.

* Site 300, an area east of the Livermore site that has been used since 1953 for testing non-nuclear, high-explosives compounds, was also declared a Superfund site in 1990. However, all discussions in this article are related to groundwater modeling and remediation at the Livermore site.

What Is a Model?

A conceptual groundwater model begins as a collection of information about the system's material properties. That information then becomes a mathematical description of an existing groundwater system, coded in a programming language, together with a quantification of the system's boundary conditions, parameters, and internal sources and sinks of groundwater and contaminants. Sometimes confusingly, the computer code used to simulate the groundwater system is also referred to as a groundwater model. So the word "model" is sometimes used for the description of the system under study and sometimes for the computer code that generated the description.

Groundwater modeling is a process of mathematically analyzing the mechanisms and controls of groundwater systems and the policies, actions, and designs that may affect these systems. Models help researchers understand subsurface fluid flow and fluid-related mass-transfer and transformation processes. They are also of use in analyzing the responses of subsurface systems to variations in both existing and potential new stresses, e.g., pumping out contaminated groundwater or returning treated groundwater to the subsurface. Modeling is an effective tool for screening alternative remediation technologies and strategies; the resulting "what-if" simulations are helpful for finding the most efficient, cost-effective methods for remediating groundwater contamination. By looking at many variables in various combinations, modeling sometimes point the way to nonintuitive ways that complex systems respond to stress and may, thus, lead to new well field designs and remediation strategies.

and analyzing a variety of data, and as modeling methods have become more sophisticated, models have been the key to refining the scope of the cleanup work. Cleanup efforts can be targeted more precisely, thereby reducing the scope of the project and saving both time and money.

Table 1. Estimated cleanup time decreases as the realism of our conceptual models improves*

	Simple "Tank" Model	2-D CFEST Model	3-D CFEST Model
Date	1990	1992–1994	1995–1996
Time to MCLs (5 ppb)	80 years	75 years	Approximately 30 years
Time to risk-based remediation (25 ppb assumed for this example)	35 years	40 years	10 to 15 years

*Applies to remediation of volatile organic compounds in distal contaminant plumes whose source of contamination has been controlled.

Notes:
MCLs = Maximum Contaminant Levels. These are the maximum levels currently allowed by regulatory agencies. ppb = parts per billion. CFEST is a finite-element, flow-and-transport model used in the remediation industry.

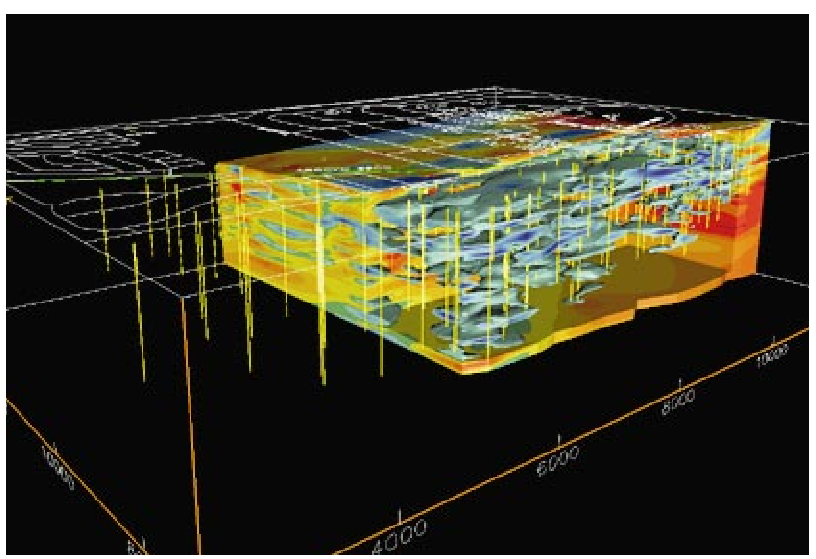


Figure 2. This visualization of core sample data represents part of the first step in developing a conceptual model. Subsurface connectivities, which show how groundwater moves, have not yet been developed in this step.

For example, in 1987 when the Laboratory was placed on the Superfund list, little modeling had yet been done. Our early simulations using a very simple model indicated that if we took no action to remediate the contamination, volatile organic compounds would spread throughout the Livermore basin in 500 to 800 years and become sufficiently diluted as to no longer be a problem. However, this "no action case" precluded many uses of the groundwater in the Livermore basin during that time period. Subsequent modeling efforts, which have improved in their physical realism over time and are based on remediating the contamination using the latest cleanup technologies, have reduced the time frame considerably, as shown in Table 1. Today, using state-of-the-art, three-dimensional modeling, a risk-based approach to groundwater cleanup, and accelerated cleanup of source regions, we can greatly reduce the estimate for successful remediation of contamination.

Conceptual Modeling

The first step in the modeling process is to develop a conceptual model, which is the initial representation of the subsurface, including both the saturated and unsaturated groundwater zones. This conceptual model incorporates all field data and laboratory measurements—a huge quantity of material. At Livermore, hundreds of monitor wells both on site and off provide information about groundwater elevations and contaminant concentrations, distribution, motion, and natural degradation. Thousands of core samples provide geologic data. We have extensive geophysical logging and seismic information, data on geochemical properties and reactions underground, and information about quantities of contaminants removed by groundwater pumping at extraction

wells, by dynamic steam stripping, and by soil vapor extraction above the water table (Figure 2).

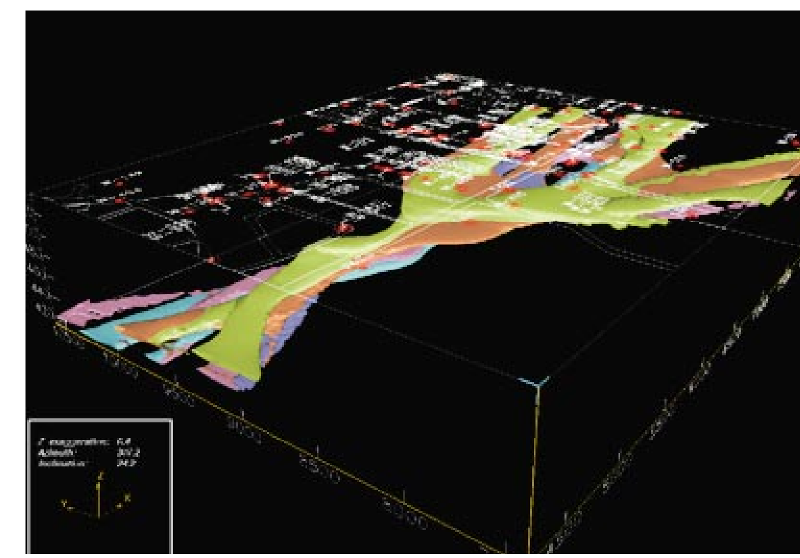
But even with all this characterization information to apply to the conceptual model, data are still insufficient to generate a highly resolved conceptual model for groundwater remediation because the subsurface is not uniform. For instance, a core sample taken at point A indicates soils with hydraulic conductivity, diffusion, and absorption properties that are very similar to those of a core sample taken at point B, 30 meters away. The soils between those two points may or may not be similar. Soils have been laid down and rearranged unevenly over millennia, and tiny fingers and braids of different soil types intermingle. Each type of soil has different, nonuniform properties that govern how quickly or slowly contaminants can travel through that soil.

A time-honored method of making up for missing data is to interpolate. Another method of filling in these data gaps is inverse modeling, a mathematical method of backing into missing data, which is used in many scientific disciplines where a lack of detailed data is a problem. Measured patterns of groundwater flow and contaminants transmitted through the Earth's subsurface can be used to back-calculate soil properties with a variety of inverse solution methods.

The conceptual model, which relies in part on interpolated data, also incorporates hydrostratigraphic analysis, a process described in the January/February 1996 issue of *Science & Technology Review*.[1] Hydrostratigraphic analysis integrates chemical, hydraulic, and geologic data and includes exhaustive trend analyses performed to produce a map of subsurface connections that indicates where contaminants can and cannot travel. Hydrostratigraphic analysis was borrowed from the oil and gas industry where it is used to determine the best way to exploit underground reserves. It is fairly new to groundwater modeling but has proven to be an effective tool in the modeling process.

This composite of actual and interpolated or back-calculated data is used to create the conceptual model in a mathematical description, or modeling code, that simulates what is happening in the subsurface. But the conceptual model is still not final because many valid interpolations are possible. So the next step is to test the model and calibrate it. As new field data become available, they are compared with the modeling code simulations. If the simulations do not match reality, then the conceptual modeling process continues until simulated and field data come into agreement. This calibration part of the modeling process, known as circular modeling, is essential to develop the best picture possible of how the subsurface behaves (Figure 3).

(a)



(b)

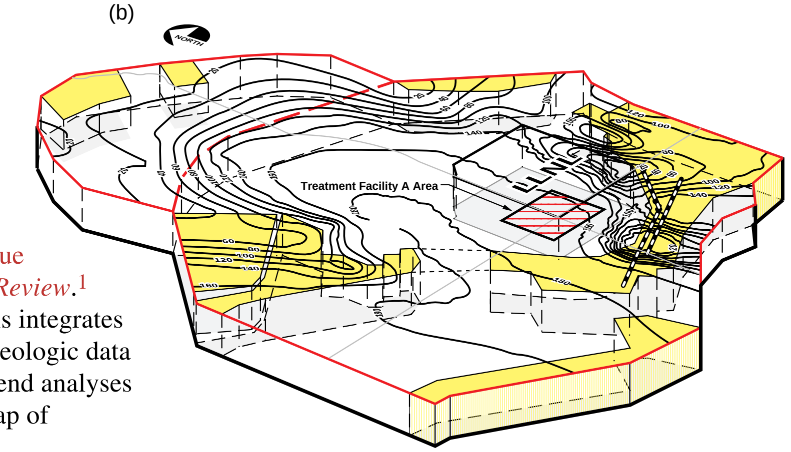


Figure 3. (a) The three-dimensional conceptual model of the hydrostratigraphic units around Treatment Facility A in the southwest corner of the Livermore site shows the underground streambeds through which groundwater moves. The three-dimensional model presents considerably more information about the subsurface than does (b) the two-dimensional model of the Livermore basin.

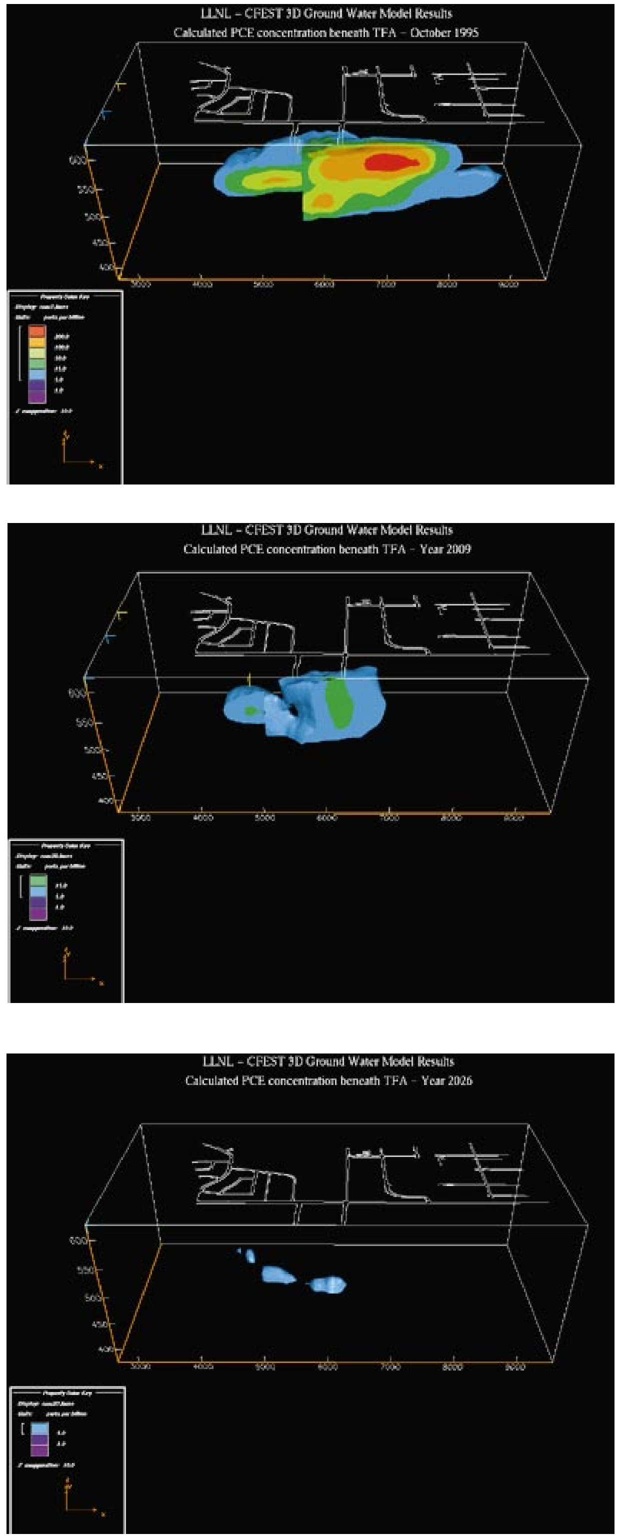


Figure 4. We used the three-dimensional CFEST modeling code to forecast the decline in concentrations of perchloroethylene (PCE), a volatile organic compound, beneath Treatment Facility A (TFA) in the southwest corner of the Livermore site. The decline shown in the simulations at the right for the years 1995, 2009, and 2026 assumes that the source of contamination for this distal contaminant plume has been controlled and that "smart" pump-and-treat cleanup methods continue for the duration. The PCE mass removed in these three dimensional simulations agrees closely with measured PCE removal.

Forecasting the Future

Groundwater modeling is very useful for estimating what will happen to the subsurface in the future (Figure 4). What will the contaminant plumes look like and where will they be in 10, 30, or 100 years if we do nothing? If we do make efforts to remediate the contamination, how will the underground environment respond to manmade changes in the subsurface? What will happen to the contaminant plumes when groundwater is pumped out? What will happen to the surrounding soils and groundwater? Is it beneficial for the cleanup effort to return treated groundwater to the subsurface? Will fuel hydrocarbons degrade naturally without posing unacceptable risks to Laboratory personnel and the public? Where should additional wells be located and what should be the rates of extraction and injection? And most important: how long will it take to clean up the groundwater to meet regulatory requirements?

Modeled simulations with the calibrated conceptual model can be very effective in helping to answer these questions. The more accurate the calibrated conceptual model, the more accurate the model forecast simulations will be.

From 1-D Models to 3-D

Simple questions about the subsurface can often be answered using dimensionless or one-dimensional conceptual models. Two-dimensional conceptual models, on the other hand, provide a better framework for organizing and relating geologic, hydrogeologic, and chemical information. Two-dimensional models give scientists, the public, and regulators a more realistic picture of the general behavior of flow and contaminant migration processes; remediation optimization and risk analysis issues are more visible; the importance of degradation and reaction processes ismore evident; and cleanup times and capture zones can be estimated.

But because our world has three dimensions, two-dimensional models have their limitations. In two-dimensional models, vertical variations in contaminant concentrations and soil hydraulic properties are averaged out, potentially overestimating the time necessary to clean up a site (Figure 5). In groundwater remediation, time equals money, so overestimating time also means running up the cost of the cleanup with untargeted well field designs and perhaps wasting taxpayer dollars.

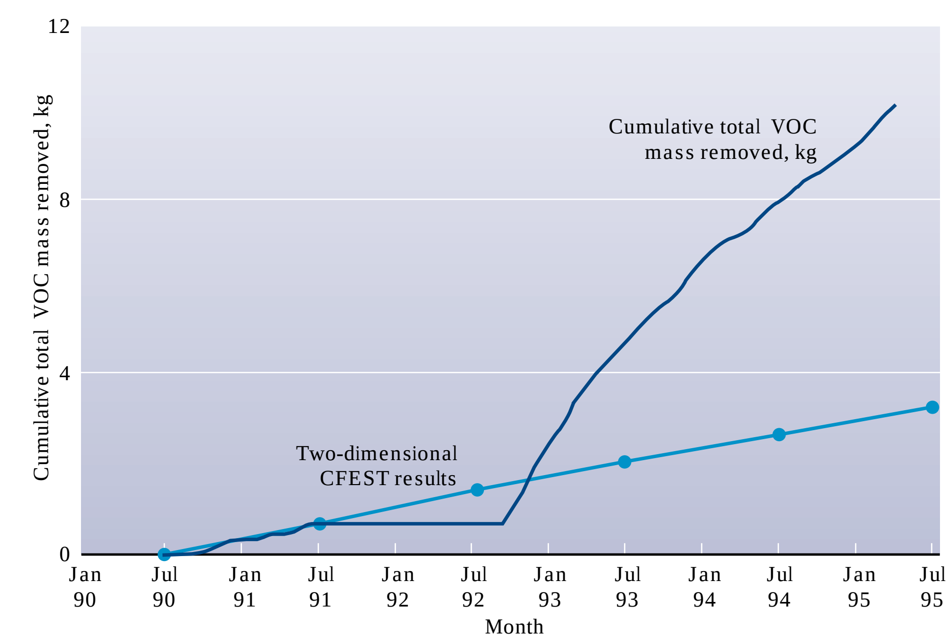
Three-dimensional conceptual models are traditionally time-consuming and costly to implement manually in groundwater modeling codes, but with new software tools, we have made considerable advances in their use. Because three-dimensional models are more representative of the real world, we can incorporate three-dimensional hydrostratigraphic representations and more effectively assess cleanup strategies, costs, and impacts. Wells can be targeted for cleanup of specific volatile organic compounds (VOCs). Three-dimensional modeling can also be used to develop targeted implementation strategies for such new technologies as dynamic underground stripping, abiotic reduction, and microbial filters.

Laboratory Innovations

The Laboratory has initiated a number of significant developments in groundwater modeling. For example, we use a variety of simulation modeling codes, each of which has its own "mesh" system for accepting such conceptual model data as conductivity, thickness, and hydraulic head. The mesh frequently must be modified to improve accuracy in simulations, to modify the conceptual models, and to resolve remediation-stressed conditions. Manually translating, or "mapping," conceptual model data to a particular mesh was a very tedious, time-consuming process and one that was prone to error, even for two-dimensional models. With three-dimensional models, mapping onto millions of mesh nodes would be almost impossible without electronic tools. While some mapping tools did exist, they were designed to be used with a specific modeling code and allowed for little geological complexity.

As a result, Lawrence Livermore is developing MapIt, which can map all conceptual model data onto any mesh so that it can be used by virtually any

Figure 5. A two-dimensional simulation using the CFEST modeling code underestimated the total volatile organic compound (VOC) mass that would be removed at Treatment Facility B, which is on the west side of the Livermore site. The three-dimensional simulation predicted that by April 1995, we would have removed approximately 3.25 kg of VOC mass whereas we had in fact removed over 10 kg from the actual three-dimensional subsurface.



modeling code (Figure 6). Two modeling codes that use different mesh systems can now be used for simulations using the same conceptual model data, and they can then be compared in more meaningful ways. MapIt includes a "feature" database that provides for considerable geologic complexity. MapIt is easy to use and allows the user to view and manipulate the features in the conceptual model as well as the graphical representation of the simulation model. Another benefit of MapIt is its use of an electronically encoded, time-stamped conceptual model, which encourages the use of consistent conceptual models across all modeling efforts.

We have also developed PLANET (Pump Layout and Evaluation Tool), an interactive software package that gives environmental remediation planners at any site the ability to quickly evaluate a large number of remediation scenarios as part of an overall strategy of hydraulic management. PLANET provides a simple, site-map-oriented interface to industry-standard flow-and-transport modeling codes. Within PLANET, a series of chemical transport simulations can be interactively designed and displayed to examine the migration of existing contaminant distributions in the saturated zone, under natural conditions, as well as under various proposed remediation scenarios. PLANET can be adapted for use with either two-dimensional or three-dimensional modeling codes.

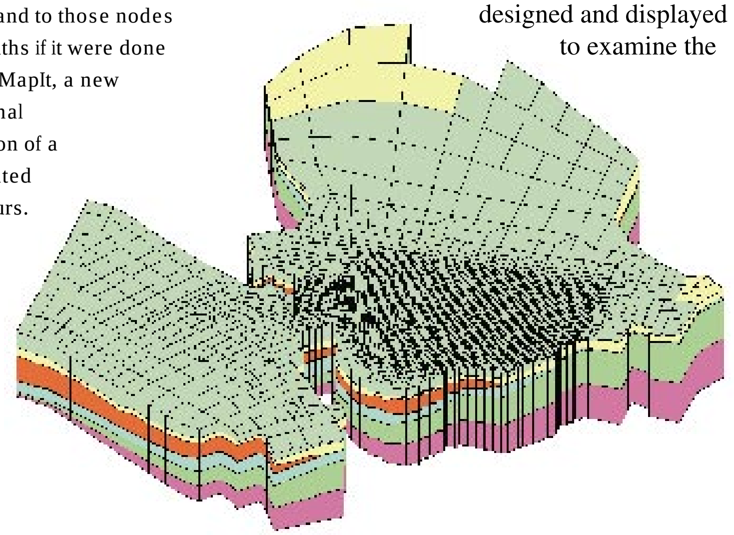


Figure 6. The huge number of nodes on the mesh for the three-dimensional conceptual model of the Livermore basin illustrates the usefulness of MapIt for mapping conceptual model data to a mesh. Mapping soil conductivity, thickness, hydraulic head, and other data by hand to those nodes would take months if it were done manually. With MapIt, a new three-dimensional conceptualization of a site can be created in just a few hours.

Artificial neural networks allow us to make use of optimization techniques that were not possible in the past because the evaluation of thousands of alternatives was so time consuming. ANNs' ability to evaluate thousands of designs per second compares to the 3 to 4 hours that a modeler normally requires to simulate a single design at a common Unix workstation not equipped with ANNs. In a small-scale trial of the ANN approach, we analyzed 28 potential extraction and injection well locations that had been selected by hydrogeologists as capable of containing and cleaning up the groundwater contamination at Livermore within 50 years (Figure 7).

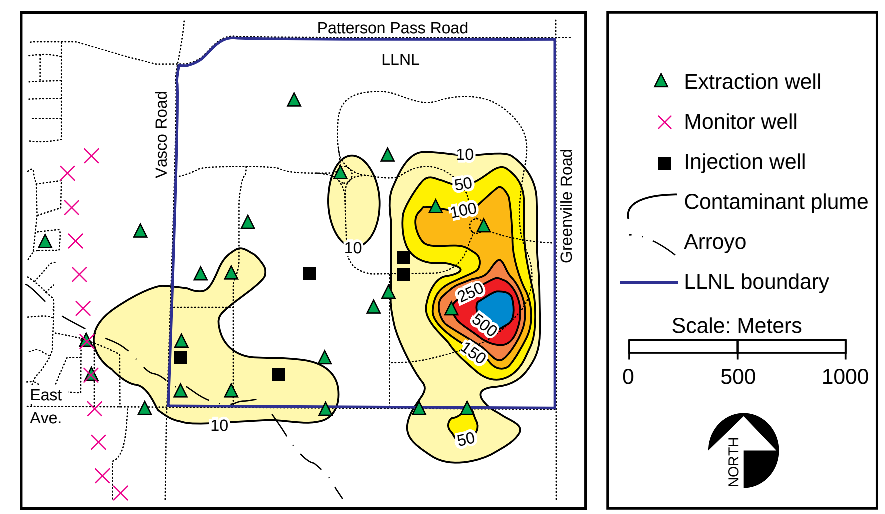
We were trying to identify the least expensive subset of these 28 locations that would prevent the spread of contaminants and remove as much as the full 28-location strategy. After using ANNs to evaluate 4 million of over 268 million possible subsets, we found acceptable strategies that involved as few as 8 to 13 locations and yet met containment and contaminant-removal goals. Installation, maintenance, and treatment costs associated with these strategies were less than 35% of those for the 28-location strategy. We now apply the ANN approach to well fields containing up to 268 potential locations and search for the optimal answers to a wide variety of management questions.

Modeling on the Internet

To facilitate widespread access to our remediation data, the Laboratory's Environmental Restoration Division now has a home page on the World Wide Web that provides authorized users access to a wealth of accumulated data. Not only can users view and download static documents, images, and product and technology overviews, but they also have access to up-to-date project status information, statistical processing capabilities, database information, and estimating tools. At their desktop computer, they can view HotMap, which provides a variety of information on any well or combination of wells at the Livermore site, or they can use PLANET, MapIt, or PDEase, a partial differential equation solver for inverse modeling (Figure 8). For the first time, Laboratory scientists and federal and state regulators have quick, timely access to data in a form that is useful to them.

Looking Ahead

Three-dimensional groundwater modeling is proving its usefulness on a regular basis, and it is still in its infancy.



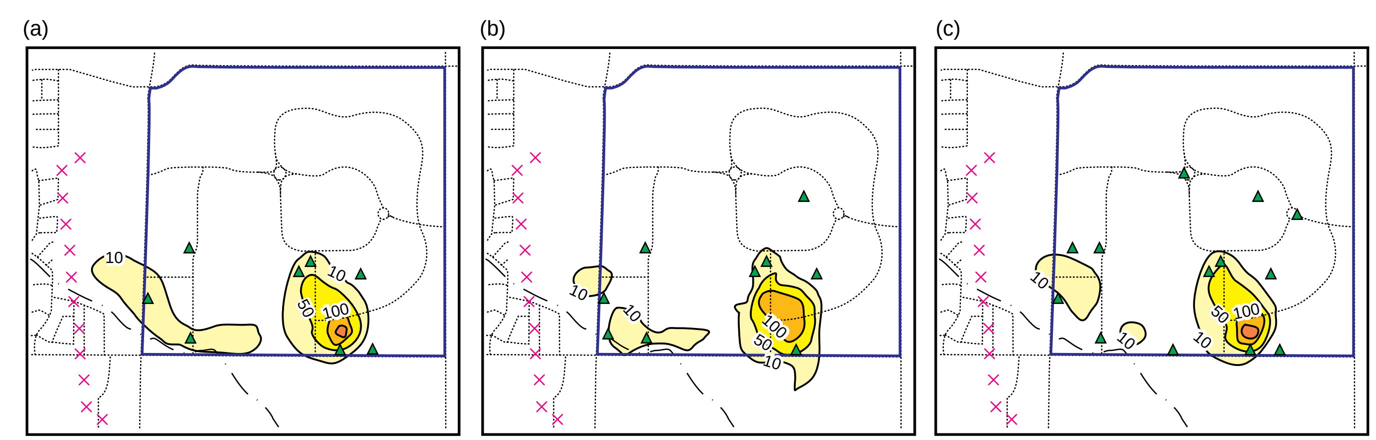


Figure 7. We use artificial neural networks (ANNs) and genetic algorithms to greatly accelerate the identification of optimal groundwater cleanup strategies. The larger figure represents the initial distribution of volatile organic compounds (VOCs) and the locations of 28 extraction and injection wells. The smaller three figures are the top-ranked patterns found after evaluating 4 million designs. The contours show VOC concentrations remaining after 50 years. Percentages in the table use the cost and performance of the full 28-well pattern as a point of reference. These evaluations are based on two-dimensional simulations of groundwater behavior.

	(a)	(b)	(c)
Number of locations	8	9	13
Contaminant contained?	Yes	Yes	Yes
Percentage of contaminant removed	97%	98%	105%
Cost relative to baseline	26%	31%	34%

Advancing computer technology and our continued creativity are key to the further advancement of groundwater modeling at the Laboratory for beneficial use everywhere. It is interesting to note that the personal computers that can be bought off the shelf today are as powerful as the Cray 1 supercomputers of less than 10 years ago. As computers become ever more powerful, our modeling capabilities can only expand for effective global applications.

Key Words: artificial neural network (ANN), genetic algorithm, groundwater contamination, groundwater remediation, hydrostratigraphic analysis, inverse modeling, volatile organic compound (VOC).

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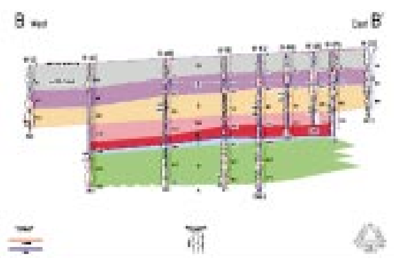
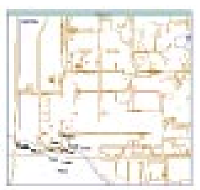
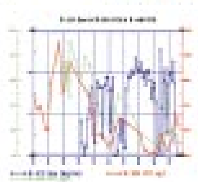
1. "Groundwater Cleanup Using Hydrostratigraphic Analysis," *Science & Technology Review*, UCRL-52000-96-1/2 (January/February 1996), pp. 6-15.

For further information contact Robert J. Gelinas (510) 423-2267 (gelinas1@llnl.gov). Information on flow and transport modeling is also available from Peter McKereghan of Weiss Associates (510) 450-6151. Virginia Johnson (510) 423-2005 (vmjohnson@llnl.gov) is a Laboratory expert on ANNs and genetic algorithm optimization.







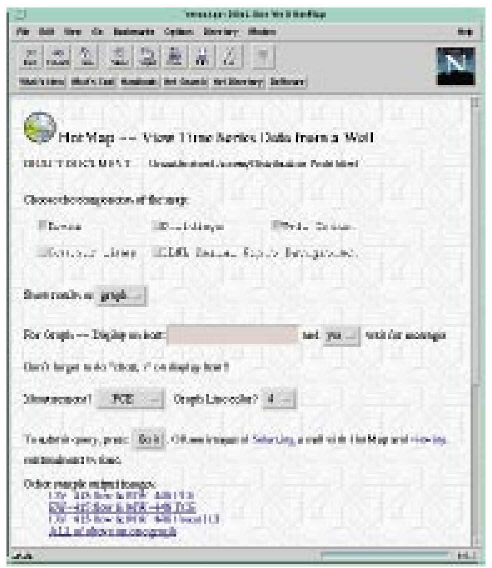


Figure 8. From the HotMap menu, an authorized user is linked to an array of information about the Livermore site.

About the Scientist

ROBERT J. GELINAS joined the Laboratory's Theoretical Physics Division in 1966 as an applied physicist. He received his Ph.D. (1965) and an M.S.E. (1961) in Nuclear Engineering and a B.S.E. (1960) in Chemical Engineering from the University of Michigan. He is currently the Environmental Transport Group Leader in the Environmental Restoration Division of the Environmental Protection Department. His experience includes leading groups of scientists and engineers in energy, defense, environmental, and high-power laser projects at both LLNL and in commercial R&D, where he was principal scientist and manager of the Science Applications International Corporation facility in Pleasanton, California, from 1975 to 1985. Gelinas has published extensively in the fields of reactive fluid flow and transport, with applications to radiative weapons systems, atmospheric and subsurface environments, high-average-power and Nova-class lasers, hydrocarbons, nuclear systems, and nuclear weapons effects.

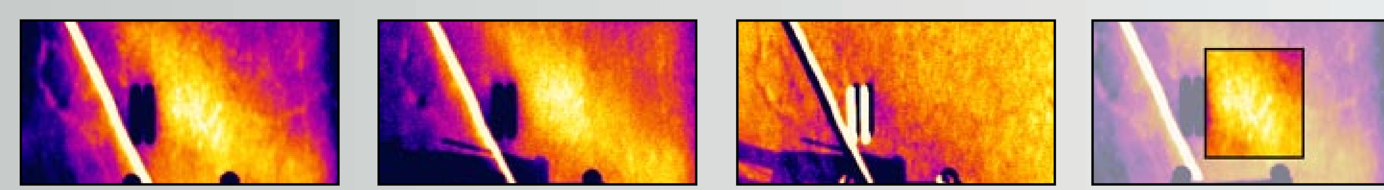
Dual-Band Infrared Computed Tomography: Searching for Hidden Defects

Dual-band infrared computed tomography systems developed at Lawrence Livermore are providing highly sensitive and accurate three-dimensional nondestructive inspection and evaluation of manmade structures in a variety of applications inside and outside the Laboratory.

PICTURESQUE bridges such as the recently famous ones in Madison County, Iowa, have secured a fond place in American hearts. But the fact is that many of them and their less attractive fellows are badly in need of repair. Federal highway officials estimate that 20% of the country's half-million two-lane bridges are structurally deficient.

Beginning in April 1996 and continuing through the summer, a converted motor home will roam the highways in several states, testing a system developed at Lawrence Livermore that can pinpoint the flaws in these well-traversed and rapidly aging bridges. Funded by the Federal Highway Administration (FHWA), this dual-band infrared (DBIR) system uses a technique known as dual-band infrared computed tomography (DBIR-CT), which locates defects in materials by sensing time-dependent temperature differences. (See the box on p. 25 and the images below.) Our system promises to make bridge inspections more reliable, faster, and safer. It also has a wide range of nondestructive inspection and evaluation applications, including unmasking metal corrosion in aircraft skins, assessing structural damage in reinforced concrete buildings, analyzing the integrity of containers of radioactive waste, and identifying corrosion in exposed petrochemical pipelines.

(Above) The dual-band infrared (DBIR) laboratory that the Federal Highway Administration is currently using for bridge inspection is a converted mobile home. The mobile DBIR laboratory's cameras, mounted about 4 meters (13 ft) above the roadway, scan the reinforced-concrete bridge deck for defects called delaminations. (Below) Delaminations are seen at the center of (a) the 8- to 12-micrometer (μm) longwave thermal infrared image and (b) the 3- to 5-μm shortwave image, both of which also show clutter. Clutter is identified in (c) the spectral difference map and later removed from (a) and (b) to create (d), which clearly shows only the delamination (minus clutter) as the bright yellow area with anomalous heat flow at the center of this image where temperatures are about 2°C warmer at noon and 0.4°C cooler at midnight.



(a) (b) (c) (d)